Spray Losses and Partitioning of Water Under a Center Pivot Sprinkler System

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ABSTRACT

CENTER pivot irrigation is extensive in the Great Plains agricultural region. The efficiency of a center pivot sprinkler system was analyzed by monitoring spray losses under various climatic conditions and by examining the partitioning of water within a corn (*Zea mays* L.) canopy. Average spray losses were 12% in 1980 and 16% in 1981. Spray losses were significantly correlated with vapor pressure deficit ($r_{x,y} = 0.49$), temperature ($r_{x,y} = 0.47$) and a wind-vapor pressure deficit term ($r_{x,y} = 0.45$). The unexplained variability in the data may be attributed to the difficulty of determining the exact application rate at a particular area of the field and to the interaction between climatic conditions and wind orientation relative to the sprinkler lateral.

Under full canopy condition in corn, about half of the water reaching the soil surface is via stemflow with the remainder falling or dripping through to the soil surface. We found 2.7 mm of canopy storage in a full corn canopy. Net loss of plant intercepted water depends on the temperature and on the ratio of canopy (r_c) and aerodynamic (r_a) resistances to vapor flux, with net losses being small if r_c/r_a is low and temperatures are high.

INTRODUCTION

Center pivot sprinklers are an important irrigation system in the Great Plains of the United States. Several thousand systems have been installed since the early 1950's because irrigators felt they offered improved efficiencies over existing surface irrigation methods, lower labor requirements, and greater management flexibility. Development of center pivot systems opened up new areas to irrigation, allowing development in regions that have soil types and topographies unsuitable for surface irrigation methods. However, sprinkler irrigation systems are more capital and energy intensive than surface systems. Rapid increases in energy costs and interest rates are causing irrigators and researchers to examine closely the efficiencies of center pivot systems.

Spray losses and plant interception losses are unique to sprinkler irrigation and must be evaluated in order to compare the efficiency of sprinklers and other types of irrigation. Christiansen (1942) did some of the earliest work to evaluate spray losses in California. He found spray losses from a single nozzle ranging from 10 to 40%. These losses were correlated with solar radiation and may have included high losses from the catch cans (Carran, 1976). Mather (1950) evaluated spray losses in New Jersey from high and low output nozzles. evaporation rates were similar from the two systems, but losses from the low output system represent a much higher percentage of pumped water. He found reduced ET rates downwind from the edge of the irrigated area. Wiersma (1955) found spray losses to be related to windspeed. Frost and Schwalen (1955 and 1960) and Frost (1963) did extensive evaluation of spray losses in Arizona. Their early experiments (Frost and Schwalen, 1955) related increased spray losses to increased vapor pressure deficit, wind velocity, and nozzle pressure and decreased nozzle size. The measured losses were most directly related to vapor pressure deficit. Clark and Finley (1975) measured spray losses in the Texas panhandle. They found losses to be generally less than 10% when windspeed was less than 4.5 m/s and to be related to both vapor pressure deficit and wind velocity. For windspeeds above 4.5 m/s, losses increased exponentially as windspeed increased, to almost 30%. Kraus (1966) found spray losses of 3 to 17% when the vapor pressure deficit ranged from 0.4 to 2.2 kPa. Drift losses comprised 36% of the total losses.

All of the water which evaporates or drifts from the sprayed area is not a net loss, because these losses offset ET losses which would have occurred in an unsprinkled field. Mather (1950) alluded to the fact that evaporation rates are reduced downwind from sprinkled areas. Frost and Schwalen (1960) measured ET from sprinkled and unsprinkled lysimeters containing grasses, clover, and alfalfa and found that ET from unsprinkled, well-watered, transpiring crops equalled or exceeded ET from sprinkled areas, over the same time period. Frost (1963) found ET rates from sprinkled areas to be less than from unsprinkled sudan grass in summer daytime measurements. Cloud cover reduced ET from dry areas more than from wet areas. Wiser et al. (1961) found sprinkler evaporation rates comparable to model estimates of potential ET. Kraus (1966) attributed reduced transpiration rates in sprinkled areas to a reduced vapor pressure deficit following sprinkling.

Water which is intercepted by the plant canopy is often considered a loss under sprinkler systems. However, just as there is reduced transpiration during periods of sprinklng and spray evaporation, there is also reduced

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transpiration during the period when water evaporates from the plant surfaces. Gross interception losses include all of the water which is stored in the plant canopy during sprinkling or precipitation. If the evaporation rate of intercepted water is similar to the ET rate from an unsprinkled area of the field, then the net loss is near zero. The net loss is equal to the amount of water which evaporates at a rate greater than that which would occur in an unsprinkled field.

Very few reports of plant intercepted water for a corn crop are reported in the literature. Stoltenberg and Wilson (1950) measured interception losses of 0.64 mm using a weighing technique that involved moving the plants. Rijtema (1965) reported a canopy storage of 1.8 mm in grass. Clark (1940) reported canopy storage capacities of 2.3, 1.8, 1.6, and 0.8 mm for his bluestem grass, clover, buffalo grass, and sudan grass, respectively.

Monteith (1981) and Rutter (1975) describe ET from a wetted canopy, relative to ET from an unwetted canopy, as a function of the ratio of canopy to aerodynamic resistances of the unwetted canopy. In herbaceous canopies, with relatively high aerodynamic resistances, the ratio is small and the effect of sprinkling on ET rates can be small. This approach is validated by comparisons of evaporation rates from wet and dry canopies reported in the literature. Burgy and Pomeroy (1958), Frost (1963), Frost and Schwalen (1960), Heermann and Shull (1976), McIlroy and Angus (1964), McMillen and Burgy (1960) and Rijtema (1965) all report comparable evaporation rates from wetted crops and from well-watered, transpiring, dry herbaceous canopies. Larsson (1981), Pearce et al., (1980), and Stewart (1977) report evaporation rates from wet forest canopies (which have much lower aerodynamic resistance and therefore higher canopy to aerodynamic resistance ratios to be much higher than from dry forest canopies. Seginor (1967) found a 48% net loss of plant intercepted water in a corn crop. Waggoner et al., (1969) found that wetted corn canopies had ET rates about twice that of unwetted, transpiring canopies for about 15 minutes after sprinkling.

Pillsbury and Degan (1972) and Heermann and Shull (1976) point out that net losses are small when sprinkling transpiring, full canopies, but sprinkling a field before full cover is achieved will increase the ET rate because of increased evaporation from the soil.

A project was initiated to examine the efficiency of a center pivot system under conditions of high wind, temperature, and vapor pressure deficit which are common in the southern Great Plains. Spray losses and partitioning of water within the canopy of a corn (*Zea mays* L.) crop are evaluated in this paper.

MATERIALS AND METHOD

Data were collected at the Garden City Experiment Station in southwestern Kansas in 1980 and 1981. Fields were located on a Ulysses fine sandy loam soil (a fine-silty, mixed, mesic, Aridic Haplustoll). Our measurements were made under a center pivot sprinkler system (Zimmatic* electric drive) that is about 400 m long and irrigates about 51 ha of land. The system is nozzled with Senninger* low angle nozzles, with a pressure of 379 kPa (55 psi) at the pivot. The field was planted with Pioneer* 3183 corn on 22 May 1980 and with Pioneer* 3194 corn on 23 May 1981. Plant populations were 53,000 and 44,000 plants/ha in 1980 and 1981, respectively.

Water reaching the top of the canopy was caught in plastic rain gauges with 37 cm^2 openings, graduated to about 0.25 mm (0.01 in.). Water falling through to the soil surface was caught in plastic rain gauges with 20 cm^2 openings, graduated to the nearest 1.27 mm (0.05 in.). A light mechanical oil was used for evaporation suppression. Stable repeated readings from the rain gauges over a period of a few days indicated that the oil prevented evaporation from the rain gauges. Rain gauges were deep enough to eliminate splash errors.

Field plot arrangements for 1980 and 1981 are shown in Figs. 1 and 2. In 1980, we located 20 rain gauges along an arc in the southeast quadrant of the field at 170 m radius from the pivot point to determine the amount of water reaching the top of the canopy. In 1981, we used 12 rain gauges at each of three sites to determine the amount of water reaching the top of the canopy. Rain gauges were mounted on iron rods that were raised as the corn grew to keep them near the top of the canopy. In

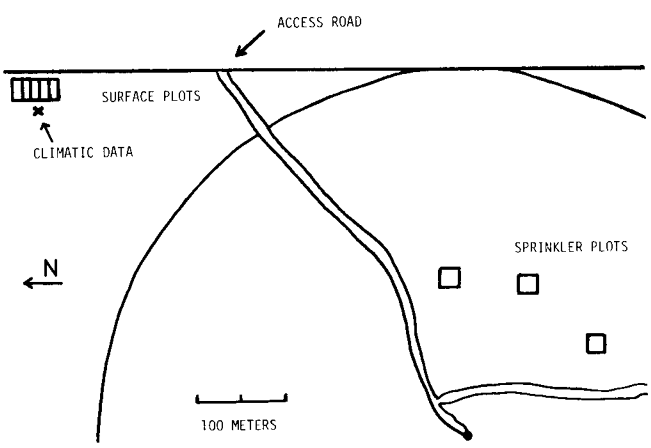

Fig. 1—Surface and sprinkler irrigated plots. Garden City, KS. 1980 and 1981.

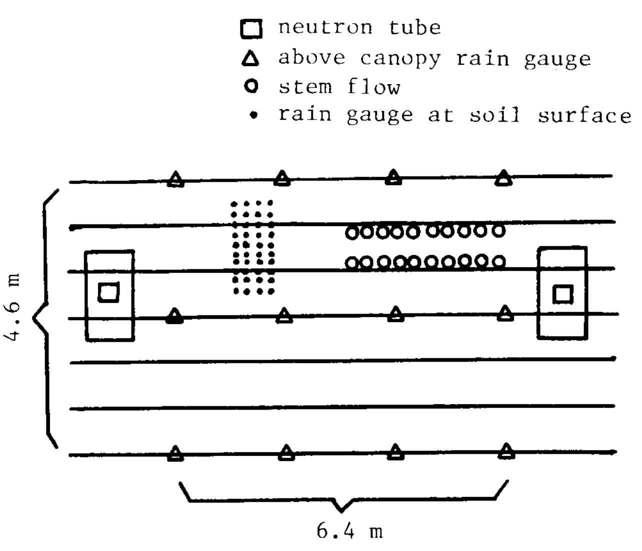

Fig. 2—Raingauge network on the sprinkler plots. Garden City, KS. 1981.

*Inclusion of trade name is for information purposes only and does not consitute an endorsement by Kansas State University or USDA-ARS.

1980 and 1981, throughfall was measured at three sites in the field in 1.1 m^2 networks of 40 rain gauges arranged at the soil surface, spanning two rows of crop from midrow to midrow. All measurements of the partitioning of sprinkled water were made midway between two towers of the center pivot system.

Stemflow was measured using acetate catchment funnels sealed around the cornstalk with silicon and wire. Captured water ran through tubing to 3.8 L holding bottles for later measurement (Fig. 3). Catchment devices extended only a few centimeters beyond the diameter of the cornstalk to minimize the capture of water falling through the corn canopy. One or two leaves were removed from the lower part of the plant to expose a smooth stalk surface before sealing the funnels to the stalks. We measured stemflow at three locations in the field on 20 plants—10 adjacent plants in two adjacent rows. Conversion of captured water volume to depth of catch was based on the soil area occupied by the 20 plants at the given location of measurement.

Application rate was determined by measuring the flow rate of water at the center of the pivot and the rate of travel of the irrigation system at a known radius. Depth of water applied, D, is calculated as:

$$D = QR^{-1}A^{-1} = \frac{\text{volume } H_2O}{\text{time}} \times \frac{\text{time}}{\text{distance}} \times \frac{\text{distance}}{\text{area}} = \frac{\text{volume } H_2O}{\text{area}} \qquad [1]$$

where Q is flow rate (m^3/h), R is the rate of movement of the pivot (m/h) and A is the area of the field watered per unit distance travelled (m^2/m). The water meter used to measure flow rate was calibrated at the Conservation and Production Research Laboratory at Bushland, Texas.

Percent spray loss, L, was calculated as the difference between the depth of water applied, D, and the depth of water caught in the rain gauges at the top of the canopy, D_n, divided by the depth of water applied.

$$L = \frac{D - D_n}{D} \times 100 \qquad [2]$$

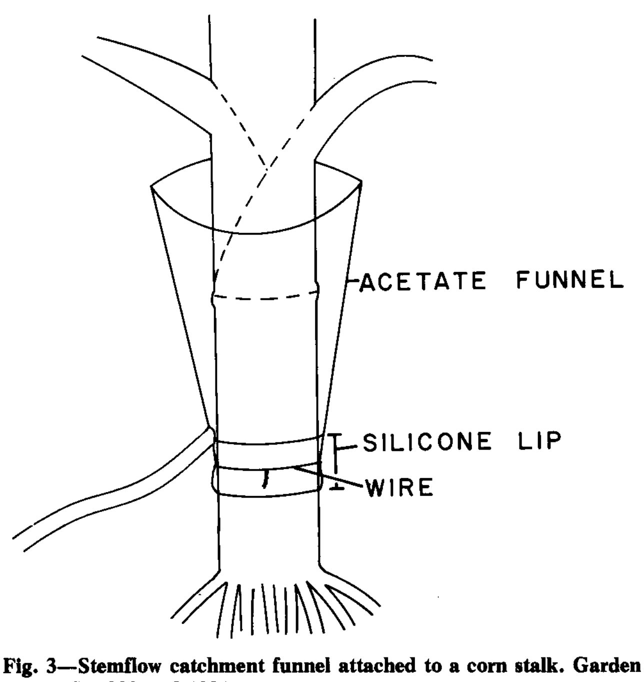

Fig. 3—Stemflow catchment funnel attached to a corn stalk. Garden City, KS. 1980 and 1981.

Plant interception of water, I_p, is calculated as the net depth of water applied minus throughfall (T), and stemflow (S), and evaporation within the canopy during sprinkling (E_c).

$$I_p = D_n - T - S - E_c \qquad [3]$$

E_c was assumed to be negligible. Norman and Campbell (1983) suggest that evaporation within the canopy and from plant surfaces during sprinkling might constitute a large portion of the total plant interception losses under high evaporative conditions. Separation of E_p and E_c is not possible with our data.

Windspeed and wind direction at a 2 m height, ambient wet and dry bulb temperature at 1.5 m, and solar radiation were measured near the research plot over an uncropped surface at 30-min intervals as shown in Fig. 1. Windspeed, wind direction, and solar radiation measurements were integrated over the scanning period. Similar data, collected about 2 km from our plots at the Garden City Experiment Station at 60-min intervals, were used, as necessary, to replace missing values in our 1981 climatic data set.

RESULTS AND DISCUSSION

Spray Losses

Table 1 and 2 summarize the water balance under a center pivot sprinkler system for 1980 and 1981. An average of about 85% of pumped water was intercepted at the top of the canopy, but the amount at different times of pumping varied considerably. Small differences in the 1980 and 1981 results may be attributed to different arrangements of rain gauges in the two years. In our experiment, no separation of droplet evaporation and wind drift was possible. A spray loss of 15% is consistent with values that Clark and Finley (1975) measured in fixed nozzle measurements.

Evaporation of spray droplets will depend upon climatic conditions at the time of pumping. Clark and Finley (1975) found that evaporation losses are related most strongly to windspeed when windspeeds exceeded 4.5 m/s and to vapor pressure deficit at lower windspeeds. In Arizona, Frost and Schwalen (1955) found that spray losses are related primarily to vapor pressure deficit in measurements at relatively low windspeeds.

Spray loss amounts from center pivot systems, particularly relating spray losses to climatic conditions at the time of pumping are not reported in the literature. Our data provide illustration of some difficulties involved

TABLE 1. PUMPED WATER (D), NET IRRIGATION (D_n), AND PARTITIONING OF WATER WITHIN THE CORN CANOPY UNDER CENTER PIVOT IRRIGATION. GARDEN CITY, KANSAS. 1980.

Date	Water pumped	Top of canopy		Throughfall		Stem flow		Plant interception
	— mm —	mm	%*	mm	%†	mm	%†	--- mm ---
7/2/80	—	21.3	—	19.3	90			
7/7	—	26.4	—	16.3	62			
7/14	34.4	27.4	79.7	12.2	44			
7/22	35.1	27.9	79.5	—	—			
7/27	32.6	32.2	98.8	12.3	38			
7/30	32.8	28.7	87.5	13.2	46			
8/1	32.4	26.7	82.4	11.7	44			
8/6	31.5	26.5	84.1	10.7	40			
8/11	31.1	27.2	87.5	14.7	52	11.7	43	1.3
8/20	31.0	32.0	103.2	13.5	42	12.2	38	6.3
9/5	—	28.9	—	16.5	58	11.7	41	0.5
Mean	32.6		87.8		52		41	2.7

* % of pumped water.
† % of water reaching the top of the canopy.

TABLE 2. PUMPED WATER (D), NET IRRIGATION (D_n), AND PARTITIONING OF WATER WITHIN THE CORN CANOPY UNDER CENTER PIVOT IRRIGATION. GARDEN CITY, KANSAS. 1981.

Date	Plot	Time on	Pumped	Top of canopy		Spray loss		Throughfall		Stem flow		Plant interception
			— mm —	mm	%*	mm	%*	mm	%†	mm	%†	--- mm ---
6/26/81	A	18:30	23.6	14.5	61.3	9.1	38.7	11.9	82.3			
	B	10:00	23.6	18.3	77.5	5.3	22.5	18.0	98.5			
	C	3:00	21.9	20.5	93.6	1.4	6.4	22.6	103.2			
7/1	A	20:30	34.7	29.5	84.9	5.2	15.1	30.4	103.3			
	B	6:30	34.7	29.7	85.6	5.0	14.4	20.8	70.1			
	C	16:30	35.9	32.8	91.3	3.1	8.7	21.6	65.8			
7/3	A		rain	23.1				19.6	84.7			
	B			23.6				19.1	80.7			
	C			23.6				21.6	91.5			
7/8	A		rain	2.0				1.0				
	B			2.0				0.8				
	C			2.3				1.3				
7/9	A	17:00	35.8	27.9	78.0	7.9	22.0	17.3	48.2			
	B	2:30	35.8	31.2	87.3	4.6	12.7	12.4	34.8			
	C	13:00	35.8	34.8	97.2	1.0	2.8	16.0	46.0			
7/17	A	4:00	34.8	28.7	82.5	6.1	17.5	16.8	58.4			
	B	13:00	34.8	27.2	78.1	7.6	21.9	—				
	C	23:00	34.8	26.2	75.2	8.6	24.8	—				
7/22[‡]	A	22:45	34.8	26.2	75.2	8.6	24.8	14.5	55.3	—		—
	B	8:45	34.8	36.1	103.6	- 1.3	- 3.6	20.1	55.6	12.7	35.2	3.3
	C	18:45	34.8	24.6	70.8	10.2	29.2	11.4	46.5	11.4	46.5	1.7
7/27	A		rain	42.7				18.3	42.8	—		
	B			42.9				19.6	45.7	—		
	C			43.2				17.8	41.2	20.8	48.2	4.6
8/1	A		rain	19.1				7.4	38.6	10.7	55.9	1.0
	B			19.6				6.1	31.1	8.4	42.8	5.1
	C			19.3				7.6	39.5	10.9	56.6	0.8
8/4	A	14:45	35.0	29.0	82.7	6.0	17.3	15.0	51.7	15.5	53.4	- 1.5
	B	4:45	35.2	32.3	91.6	2.9	8.4	9.7		10.9		—
8/3	C	18:45	35.2	28.5	80.8	6.8	19.2	12.1	42.8	12.4	43.5	4.0
8/7	A	14:45	31.5+[#]	31.5	83.8	5.1	16.2	16.8	53.2	12.4	39.5	2.3[‖]
8/6	B	22:45	31.5	31.2	99.2	0.3	0.8	11.8	35.8	—		—
8/9	B		rain	5.1		—		1.3		—		
8/6	C	13:45	31.5+	25.6	65.3	10.9	34.7	10.2	40.0	16.5	64.0	
8/13	A	22:45	33.8	29.7	87.9	4.1	12.1	13.2	44.5	14.7	49.6	1.8
	B	12:45	34.3	30.2	88.0	4.1	12.0	9.7	32.0	13.5	44.6	7.0
	C	3:15	33.2+	35.6	94.3	1.9	5.7	14.0	39.2	15.0	42.1	6.6[‖]
	A		rain	4.3				1.8	41.3	1.8	41.3	
	B			4.3				0.8		1.5		
Mean			33.0		84.0		16.0		43.2[§]		46.8	2.7

* % of pumped water.
† % of water reaching the top of the canopy.
‡ LAI = 3.0 on July 19.
§ Mean of data after full cover (LAI ⩾ 3) was reached.
‖ Interception from two wetting events.
\# '+' indicates that irrigation and rainfall readings are not separated in the rest of the table.

in attempting such a determination. Table 3 lists spray losses in 1981 and climatic conditions at the time of pumping. Correlation of spray loss to the various climatic variables is given in Table 4. We found correlation between spray loss and vapor pressure deficit, temperature, and a term combining vapor pressure deficit with windspeed at the 1, 2, and 3% level of significance. However, we can explain ony one-fourth of the variability in our data with correlation to a climatic factor. Since all significant correlations involve related climatic variables, a multiple variable model does not improve our ability to predict spray loss.

Much of the variability in our data can be explained by the difficulty of determining precisely the application rate in a specific area of the field. We measured the flow rate into the entire center pivot system rather than to a particular nozzle or set of nozzles and thus have an average application rate for the field, rather than the application rate at our data collection sites. As one moves from the center of the system outward, each nozzle (spaced evenly along the lateral) irrigates an increasing acreage and the nozzle output increases correspondingly. Depending upon the orientation of the wind direction to the pivot, a given parcel of land can receive water from either higher or lower output nozzles than normally would spray that area.

In addition, the effects of ambient climatic conditions on spray losses will be minimized if the wind is blowing parallel to the lateral. This occurs because the air mass crossing the measurement site will have been cooled and humidified while moving over the sprinkler system. With a parallel wind, conditions at the collection site are similar (low vapor pressure deficit, cool temperatures) regardless of the ambient evaporative conditions. The only time that maximal spray losses would be observed is during a cross wind and high evaporative conditions (Table 5). Three measurements taken with winds parallel to the lateral indicate very similar spray losses, even though climatic conditions at the time of pumping were quite different. Measurements taken with the wind

TABLE 3. SPRAY LOSSES, WINDSPEED (u), VAPOR PRESSURE DEFICIT (vpd), SOLAR RADIATION (R_s), TEMPERATURE (TEMP.), AND WIND ANGLE AT THE TIME OF PUMPING. GARDEN CITY, KANSAS. 1981.

Spray loss	u	vpd	R_s	Temp.	Wind angle
%	$m s^{-1}$	kPa	$W m^{-2}$	C	Degrees from lateral
- 3.6	2.25	0.40	426	21.5	31
0.8	0.51	0.24	0	19.4	66
2.8	7.78	2.02	705	31.8	65
5.7	4.34	0.08	0	19.4	10
6.4	3.98	0.46	0	21.7	32
8.4	2.12	0.33	0	21.4	51
8.7	5.29	1.11	35	29.1	61
12.0	5.52	1.08	768	27.4	84
12.1	3.16	0.33	0	22.1	27
12.7	3.45	0.63	0	21.7	51
14.4	3.60	0.14	0	20.9	1
15.1	3.41	1.23	0	25.2	30
16.2	2.86	1.84	544	27.9	2
17.3	5.16	1.97	740	33.1	19
17.5	1.77	0.31	0	20.2	3
19.2	1.58	0.96	14	27.5	32
21.9	2.58	2.64	859	32.2	81
22.0	4.19	2.14	551	31.1	41
22.5	6.19	2.47	77	31.9	90
24.8	4.89	0.33	0	20.3	85
24.8	2.76	0.48	0	23.6	70
29.2	2.04	0.85	14	25.2	28
34.7	3.47	1.20	803	28.1	9
38.7	7.73	3.49	35	35.5	76

blowing across the lateral show a response to ambient conditions with high losses measured under high evaporative conditions and low losses measured under low evaporative conditions.

Table 4 shows the correlation of spray loss to climatic variables when the data set is divided into periods with parallel and cross winds. With a parallel wind (angle ≤ 20 deg), we found no significant correlation of windspeed, vapor pressure deficit, or temperature to spray losses. A correlation of 0.73 between spray loss and solar radiation, significant at the 10% level, might be due to the correlation between solar radiation and vapor pressure deficit and temperature. With wind blowing across the system (angle ≥ 45 deg), correlation of spray loss with vapor pressure deficit and with the wind-vapor pressure deficit term was slightly higher than the correlation found in the complete data set, though the significance levels dropped with the smaller data set.

Partitioning of Water within the Canopy

Throughfall of water to the soil surface was measured throughout the irrigation season. The proportion of water reaching the canopy that falls through to the surface is very high early in the season and declines as the plant canopy develops.

Measurement of stemflow and estimation of plant interception was made only under full canopy conditions, when LAI exceeded 3.0. Almost half of the water that reached the top of the canopy reached the surface by stemflow (Tables 1 and 2). Proportions of stemflow and throughfall were similar whether water was applied as irrigation or as rainfall. Seasonal estimate of plant interception of water was 2.7 mm per wetting event in 1980 and in 1981. Plant intercepted water was determined by subtraction. Errors in measurement of water at the top of the canopy, throughfall, or stemflow can introduce large errors in the estimate of plant interception.

Canopy storage capacity of a corn crop depends on leaf area index, spacing of plants, and varietal characteristics, such as erectness and senescence of leaves. Storage capacity of a canopy will be relatively constant under full canopy conditions, but the percentage of pumped water that is stored in the canopy depends on the amount of water that is applied with each irrigation.

TABLE 5. ILLUSTRATION OF THE INTERACTION OF WIND ORIENTATION AND EVAPORATIVE CONDITIONS, RELATIVE TO SPRAY LOSS MEASUREMENT.

Wind orientation	Evaporative conditions			Spray loss
	u	vpd	T	
Degrees from lateral	m/s	kPa	C	%
90 (cross)	6.19	2.47	31.9	22.5
84	5.52	1.08	27.4	12.0
66	0.51	0.24	19.4	0.8
1 (parallel)	3.60	0.14	20.9	14.4
2	2.86	1.84	27.9	16.2
3	1.77	0.31	20.2	17.5

Evaporation of Plant Intercepted Water

Many researchers have pointed out that the evaporation of water from wetted leaves will reduce transpiration that would be occurring if the leaves had not been wetted. Monteith (1981) and Rutter (1975) describe a form of the Penman equation which expresses the rate of evaporation from wet, E_{wet}, as a multiple of the evaporation rate from a dry foliage, E_{dry}, as follows

$$E_{wet} = 1 + \left(\frac{\gamma\, r_c/r_a}{s + \gamma}\right) E_{dry} \quad [4]$$

TABLE 4. CORRELATION COEFFICIENTS OF SPRAY LOSSES AND CLIMATIC CONDITIONS. GARDEN CITY, KANSAS. 1981.

	Spray loss	u	e^u	$\sqrt{u}$	vpd$\sqrt{u}$	vpd	Temp.	R_s	Angle
(a) For all data points (n = 24)									
Spray loss $r_{x,y}$:	1.00	0.19	0.14	0.21	0.45	0.49	0.47	0.08	- 0.02
p*:	0.00	0.37	0.52	0.30	0.03	0.01	0.02	0.73	0.94
(b) Wind parrallel to lateral (angle $\leq 20°$, n = 6).									
Spray loss $r_{x,y}$:	1.00	- 0.13	- 0.11	- 0.11	0.41	0.43	0.54	0.73	0.13
p:	0.00	0.81	0.82	0.82	0.42	0.38	0.27	0.10	0.80
(c) Wind blowing across the lateral (angle > 45°, n = 11)									
Spray loss $r_{x,y}$:	1.00	0.33	0.20	0.39	0.52	0.53	0.41	- 0.17	0.52
p:	0.00	0.31	0.55	0.24	0.10	0.09	0.22	0.62	0.09

* p represents the probability of a type I error

where s is the slope of the saturation vapor pressure curve, γ is the psychrometric constant, and r_c and r_a are canopy and aerodynamic resistances, respectively. The canopy resistance is a function of the leaf properties and of the canopy structure and includes the resistance to vapor flux from individual leaves and within the canopy. Variation in stomatal resistance dominates the variability in canopy resistance of a full canopy crop. The aerodynamic resistance is a characteristic of the crop-atmosphere interface and is a function of windspeed and of the canopy structure. Since both s and γ are functions of temperature, the rate of evaporation of plant-intercepted water, relative to evaporation from an unwetted canopy, is a function of temperature and of the ratio of canopy and aerodynamic resistances.

This approach does not account for microclimatic changes that occur when sprinkling occurs. Cooling and humidification of a sprinkled canopy may lower the vapor pressure gradient between the canopy and the atmosphere, compared to an unsprinkled canopy. Useful general analysis of net interception losses from a sprinkled crop can be made, in spite of this limitation, but a detailed quantitative analysis of losses would require a more complex model, such as the one reported by Norman and Campbell (1983).

If the evaporation rate from an unwetted canopy is defined as being 100% efficient, then evaporation from a wetted canopy at a higher rate can be defined as inefficient, and would be termed a net interception loss. Fig. 4 shows relative ET rates and seasonal net interception losses calculated from [4] for wet canopies, under different temperature and resistance conditions. Sprinkling a well-watered, transpiring corn crop will have a minimal effect on ET rates, because r_c/r_a will be low and little additional water will be lost compared to an unsprinkled crop. The warmer the temperature, the less the difference in ET rates from wetted and dry canopies. Sprinkling at night, when r_c is high and temperatures are low, results in evaporation rates that are much higher than from unwetted crops and increases net interception losses. Fig. 4 shows the seasonal net interception losses that could result if all water was applied under similar climatic conditions. Sprinkling when the temperature is low and r_c/r_a is high (nighttime conditions) would result in a net interception loss of about 16 to 18 mm or 5 to 6% of the 302 mm of applied water. Sprinkling when the temperature is high and r_c/r_a is low (daytime conditions) would result in a net interception loss of 2 to 4 mm or about 1% of applied water. It must be recognized that increased net interception losses with nighttime sprinkling will be offset by much larger reductions in

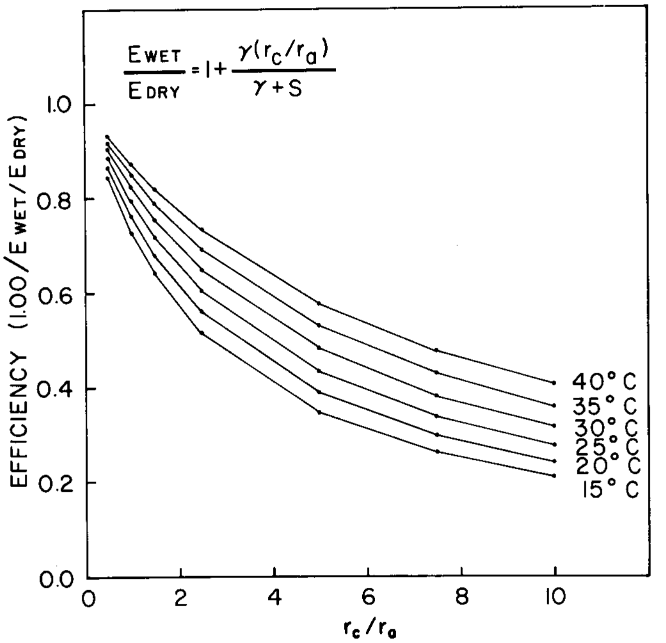

Fig. 4b—Relative evaporation rates and seasonal losses of wetted and unwetted aras of a crop canopy. (b) Efficiency of evaporation from a wetted portion of the canopy, assuming that evaporation from an unwetted portion of the canopy has an efficiency of 1.0.

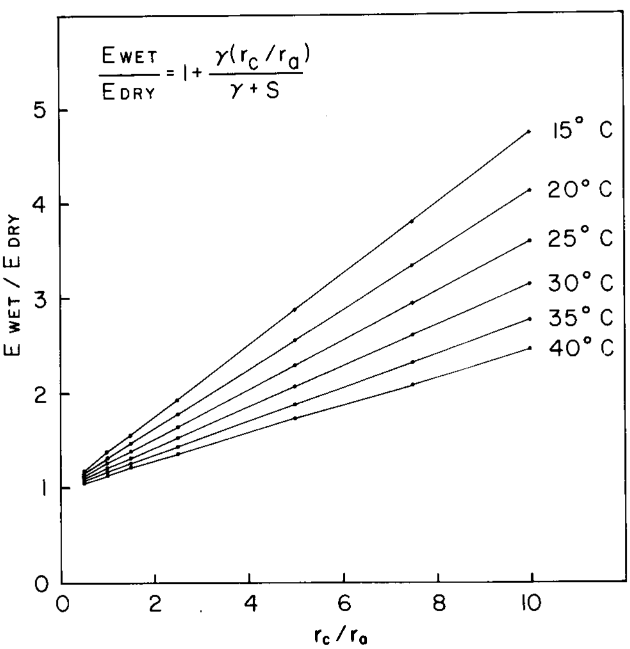

Fig. 4a—Relative evaporation rates and seasonal losses of wetted and unwetted areas of a crop canopy. (a) Evaporation from a wetted canopy as a multiple of the evaporation from a dry canopy (after Rutter, 1975 and Monteith, 1981).

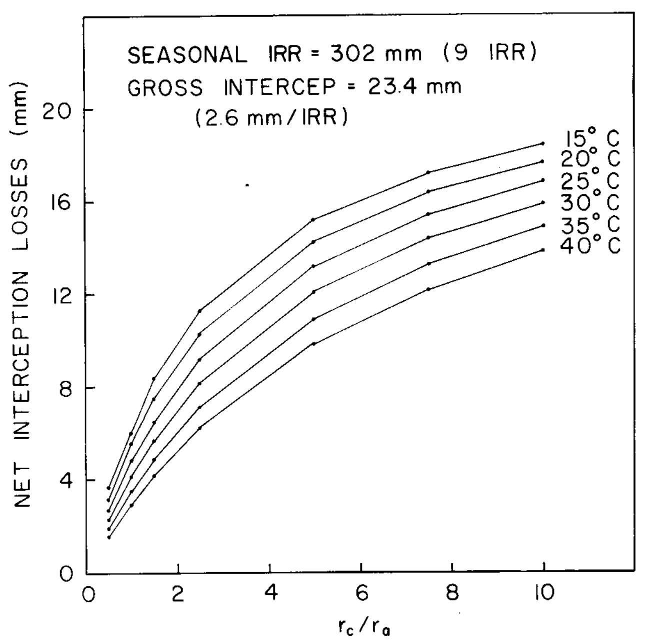

Fig. 4c—Relative evaporation rates and seasonal losses of wetted and unwetted areas of a crop canopy. (c) Seasonal interception losses from 9 irrigations under constant temperature and resistance conditions.

spray losses and that overall efficiency of sprinkling will be higher at night than in the day, particularly in areas that show large diurnal fluctuations in vapor pressure deficit and windspeed.

Under a center pivot sprinkler system that is operating under a wide range of conditions, evaporation from wetted canopies might be very efficient during the day and inefficient at night. Seasonal plant interception losses will depend on the number of irrigations, canopy cover at the time of irrigation, and amount of water applied. Net seasonal losses of plant intercepted water in a corn crop would probably be about 2 to 4% of pumped water under conditions in our experiment, with pumping occurring day and night.

CONCLUSIONS

In an efficient irrigation system, a high proportion of the applied water will be beneficially used, the crop water requirements will be met throughout the season, and water will be applied uniformly across the field, in order to satisfy the above mentioned efficiency requirements. In a sprinkler system, one must analyze spray losses and interception of water in the plant canopy in order to evaluate the irrigation efficiency. Spray losses are the major losses. We found a maximum interception loss of 2.7 mm per irrigation. The net seasonal loss would depend on the crop cover at the time of irrigation, frequency and depth of application, and the climatic conditions at the time of pumping. In general, irrigation before full canopy cover is established is less efficient than irrigation later in the season. Spray losses average about 15% under higher evaporative conditions such as are found in the southern Great Plains region. This would depend upon the sprinkler design, the depth of application, and environmental conditions at the time of pumping.

Given the influence of wind angle on the measured spray loss and of wind angle and windspeed on wind drift of droplets, it will be difficult to make measurements to determine accurately the spray losses at any given time for the whole field. Perhaps a better way to determine patterns of spray loss for the entire center pivot system will be to model the complex interactions of climatic conditions, nozzle output, wind direction, and other factors using solid set spray evaporation measurements and detailed information about the design of a specific center pivot system.

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